CHAPTER 11 – ENERGY DISSIPATOR DESIGN

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11.1 General Design Concepts

Erosive forces that are at work in the natural drainage network are often increased by construction of a highway. Interception and concentration of overland flow and constriction of natural waterways inevitably results in increased erosion potential. To protect the highway and adjacent areas it is sometimes necessary to employ an energy dissipating device. Energy dissipators should be considered part of the larger design system which includes the culvert and channel protection requirements (upstream and downstream) and may include a debris control structure. The interrelationship of these various components must be considered in designing any one part of the system. For example, energy dissipator requirements may be reduced, increased or possibly eliminated by changes in the culvert design; and downstream channel conditions (velocity, depth, and channel stability) will impact the selection and design of appropriate energy dissipation devices.

Throughout the design process, the designer should keep in mind that the primary objective is to protect the highway structure and adjacent area from excessive damage due to erosion. One way to accomplish this objective is to return flow to the downstream channel in a condition that approximates the natural flow regime. Note that this also implies guarding against employing energy dissipation devices that reduce flow conditions substantially below the natural or normal channel conditions. If an energy dissipator is necessary, the first step should be consideration of possible ways of modifying the outlet velocity or erosion potential. This could include modifying the culvert barrel. If an internal modification is not cost effective or is hydraulically unacceptable, the designer must begin the process of selecting and designing an appropriate external energy dissipation device. The following sections summarize some of the factors involved in designing an energy dissipator. For a comprehensive treatment of energy dissipator design refer to the FHWA publication HEC-14[1] (http://www.fhwa.dot.gov/bridge/hydpub.htm).

11.2 Erosion Hazards

Erosion at a culvert inlet is not typically a major problem. At the design discharge, water will normally pond at the inlet, and the only significant increases in velocity will occur upstream of the culvert a distance about equal to the height of the culvert. The average velocity near the inlet may be approximated by dividing the flow rate by the area of the culvert opening. The risk of erosion approaching the inlet should be based on this velocity estimate. Note that the erosion risk may be greater at flow rates less than the design discharge, since depth of ponding at the inlet will be less and greater velocities may occur. This is especially true in channels with steep slopes and high velocity flow.

Most inlet failures have occurred on large flexible-type pipe culverts with projected or mitered entrances without headwalls or other entrance protection. Projecting inlets can bend or buckle from buoyant forces. Mitered entrance edges can be bent in from hydraulic forces. To aid in preventing these types of failures, protective features should include concrete headwalls and/or slope paving.

Erosion at culvert outlets is a common problem. Determination of the flow condition, scour potential and channel erodibility should be standard procedure in the design of all highway culverts. Ultimately, the only safe procedure is to design on the basis that erosion at a culvert outlet and downstream channel will occur, and must be protected against.

11.3 Culvert Outlet Velocity and Velocity Modification

The continuity equation (Equation 3.1) can be used in all situations to compute culvert outlet velocity, either within the barrel or at the outlet. Given the design discharge, the only other information needed is the flow area, which is a function of the type of control (outlet or inlet).

Culvert outlet velocity is one of the primary indicators of erosion potential. Outlet velocities are seldom less than 10 ft/s and will range up to 30 ft/s for culverts on small or mild slopes, and will be even greater for culverts on steep slopes. If the velocity is higher than in the downstream channel, measures to modify or reduce velocity within the culvert barrel should be considered. However, the degree of velocity reduction is typically limited and must be balanced against the increased costs usually involved.

11.3.1 Culverts on Mild Slopes

For culverts on mild slopes operating under outlet control with high tailwater (Figures 9.11a and 9.11b), the outlet velocity will be determined using the full area of the barrel. With this condition it is possible to reduce the velocity by increasing the culvert size. Note that with high tailwater conditions, erosion may not be a serious problem since the ponded water will act as an energy dissipator; however, it will be important to determine if tailwater will always control, or if any of the other conditions shown on Figure 9.11 might occur.

When the discharge is high enough to produce a critical depth equal to the crown of the culvert barrel (Figure 9.11c), full flow will again occur and the outlet velocity will be based on the area of the barrel. As before, the barrel size can be increased to achieve a reduction in velocity, but it will be necessary to evaluate if the increased size results in a flow depth below the crown, indicating less than full flow at the outlet. When this occurs, the area used in the continuity equation should be based on the actual flow area.

When culverts discharge with critical depth occurring near the outlet (Figures 9.11d and 9.11e), increasing the barrel size will typically not significantly reduce the outlet velocity. Similarly, increasing the resistance factor will not affect outlet velocity since critical depth is not a function of n.

11.3.2 Culverts on Steep Slopes

For culverts flowing on steep slopes with no tailwater (Figures 9.3a and 9.3b) the outlet velocity can be determined from normal depth calculations. With normal depth conditions on a steep slope, increasing the barrel size may slightly decrease the outlet velocity; however, calculations show that in reality, the slope is the driving force in establishing the normal depth. The velocity will not be significantly altered by even doubling the culvert size/width. Thus, such an approach is not cost effective. Some reduction in outlet velocity can be obtained by increasing the number of barrels, but this is also generally not cost effective.

Increasing the barrel resistance can significantly reduce outlet velocity and is an important factor in velocity reduction for culverts on steep slopes. The objective is to force full flow near the outlet without creating additional headwater. HEC-14 discusses various methods of creating additional roughness, from changing pipe material to baffles and roughness rings, and details the appropriate design procedures.

11.4 Hydraulic Jump Energy Dissipators

The hydraulic jump is a natural phenomenon which occurs when supercritical flow changes to subcritical flow (see Chapter 3). This abrupt change in flow condition is accomplished by considerable turbulence and loss of energy, making the hydraulic jump an effective energy dissipation device. To better define the location and length of a hydraulic jump, standard design structures have been developed to force the hydraulic jump to occur. These structures typically use blocks, sills or other roughness elements to impose exaggerated resistance to flow. Forced hydraulic jump structures applicable in highway engineering include the Colorado State University (CSU) rigid boundary basin, USBR type IV basin and the St. Anthony Falls basin.

The CSU rigid boundary basin was developed from model study tests of basins with abrupt expansions (Figure 11.1); however, the configuration recommended for use is a combination flared-abrupt expansion basin. The roughness elements are symmetrical about the basin centerline and the spacing between the elements is approximately equal to the element width. Alternate rows of roughness elements are staggered. Riprap may be needed for a short distance downstream of the basin.

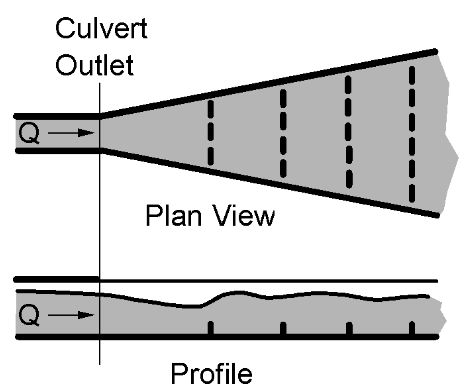

Figure 11.1a. Schematic of CSU rigid boundary basin.

Figure 11.1b. CSU rigid boundary basin.

The St. Anthony Falls (SAF) stilling basin is a more generalized design that uses special appurtenances, chute blocks and baffle or floor blocks to force the hydraulic jump to occur (Figure 11.2). It is recommended for Froude Numbers between 1.7 and 17. Similar to the CSU basin, the design criteria were developed from model study test results.

11.5 Impact Basins

As the name implies, impact basins are designed with part of the structure physically blocking the free discharge of water. The action of water impacting on the structure dissipates energy and modifies the downstream flow regime. Impact basins include the Contra Costa Energy Dissipator, Hook type energy dissipator, and the USBR Type VI Stilling Basin.

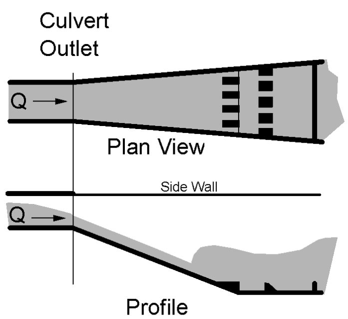

Figure 11.2a. Schematic of SAF stilling basin.

Figure 11.2b. SAF stilling basin.

The impact basin most commonly used in highway engineering is probably the USBR Type VI (Figure 11.3). The structure is contained in a relatively small box-like structure which requires no tailwater for successful performance. The shape of the basin evolved from extensive tests, and resulted in a design based around a vertical hanging baffle. Energy dissipation is initiated by flow striking the vertical hanging baffle and being deflected upstream by the horizontal portion of the baffle and by the floor, creating horizontal eddies. Notches in the baffle provide a self cleaning feature after prolonged nonuse of the structure. If the basin is full of sediment, the notches provide concentrated jets of water for cleaning, and if the basin is completely clogged the full discharge can be carried over the top of the baffle. Use of the basin is limited to installations where the velocity at the entrance of the basin does not exceed 50 ft/s and discharge is less than 400 ft^3/s.

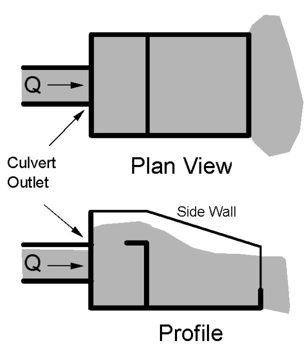

Figure 11.3a. Schematic of USBR Type VI.

Figure 11.3b. Baffle-wall energy dissipator - USBR Type VI.

11.6. Drop Structures With Energy Dissipation

Drop structures are commonly used for flow control and energy dissipation. Reducing channel slope by placing drop structures at intervals along the channel changes a continuous steeper sloped channel into a series of milder sloped reaches with vertical drops. Instead of slowing down and transferring high erosion producing velocities into lower nonerosive velocities, drop structures control the slope of the channel so that high velocities never develop. The kinetic energy or velocity gained by the water as it drops over the crest of each structure is dissipated by specially designed aprons or stilling basins.

Energy dissipation occurs through impact of the falling water on the floor, redirection of the flow, and turbulence. The stilling basin used to dissipate excess energy can vary from a simple concrete apron to an apron with flow obstructions such as baffle blocks, sills, or abrupt rises. The length of the concrete apron required can be shortened by addition of these appurtenances. Figure 11.4 illustrates a straight drop stilling basin with floor blocks and an end sill. The design of this and other drop structure stilling basins is detailed in HEC-14.(1)

11.7. Stilling Wells

Stilling wells dissipate kinetic energy by forcing flow to travel vertically upward to reach the downstream channel. The stilling well most commonly used in highway engineering is the Corps of Engineers Stilling Well (Figure 11.5). This stilling well has application where debris is not a serious problem. It will operate with moderate to high concentrations of sand and silt, but is not recommended for areas where quantities of large floating or rolling debris are expected unless suitable debris-control structures are used. Its greatest application in highway engineering is at the outfalls of storm drains and pipe down drains where little debris is expected. It is recommended that riprap or other types of channel protection be provided around the stilling well outlet.

11.8. Riprap Stilling Basins

Riprap stilling basins are commonly used at culvert outfalls (Figure 11.6). The design procedure for riprap energy dissipators was developed from model study tests. The results of this testing indicated that the size of the scour hole at the outlet of a culvert was related to the size of the riprap, discharge, brink depth and tailwater depth. The mound of rock material that often forms on the bed downstream of the scour hole contributes to dissipation of energy and reduces the size of scour hole. The general design guidelines for riprap stilling basins include preshaping the scour hole and lining it with riprap. Specific design criteria for the length, depth and width of the scour hole, and the entire basin, are provided in HEC-14.(1)

11.9. Energy Dissipator Design Using HY-8

Energy dissipator design for culvert outlets can be completed with HY-8 (www.fhwa.dot.gov/bridge/hydrain.htm). The design is based on FHWA publication HEC-14.(1) Table 11.1 provides guidelines for the use of various energy dissipators described in HEC-14. A performance curve is necessary for any energy dissipator design and analysis.

Figure 11.4. Straight drop spillway stilling basin.

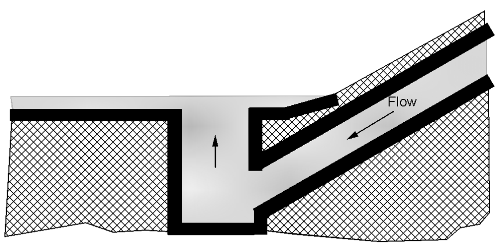

Figure 11.5a. Schematic of COE stilling well.

Figure 11.5b. COE stilling well.

Figure 11.6. Riprapped culvert energy basin.

Table 11.1 Energy Dissipator Limitations (source Table XII-1, HEC-14).[1]

Dissipator Type	Froude Number Fr	Allowable Debris			Tailwater TW	Special Consideration
		Silt Sand	Boulders	Floating		
Free Hydraulic Jump	>1	H	H	H	Required	--
						--
CSU Rigid Boundary	<3	M	L	M	--	--
Tumbling Flow	>1	M	L	L	--	$4<S_o<25$
Increased Resistance	--	M	L	L	--	Check Outlet Control HW
USBR Type II	4 to 14	M	L	M	Required	--
USBR Type III	4.5 to 17	M	L	M	Required	--
USBR Type IV	2.5 to 4.5	M	L	M	Required	--
SAF	1.7 to 17	M	L	M	Required	--
Contra Costa	<3	H	M	M	<0.5D	--
Hook	1.8 to 3	H	M	M	--	--
USBR Type VI	--	M	L	L	Desirable	Q<400 cfs, V<50 fps
Forest Service	--	M	L	L	Desirable	D<36 inch
Drop Structure	<1	H	L	M	Required	Drop< 15 ft
Manifold	--	M	N	N	Desirable	
Corps Stilling Well	--	M	L	N	Desirable	
Riprap	<3	H	H	H	--	

Note:

N = none
L = low
M = moderate
H = heavy

References

1. Federal Highway Administration, Hydraulic Engineering Circular No. 14, *Hydraulic Design of Energy Dissipators for Culverts and Channels*, FHWA EPD-86-110, 1983.